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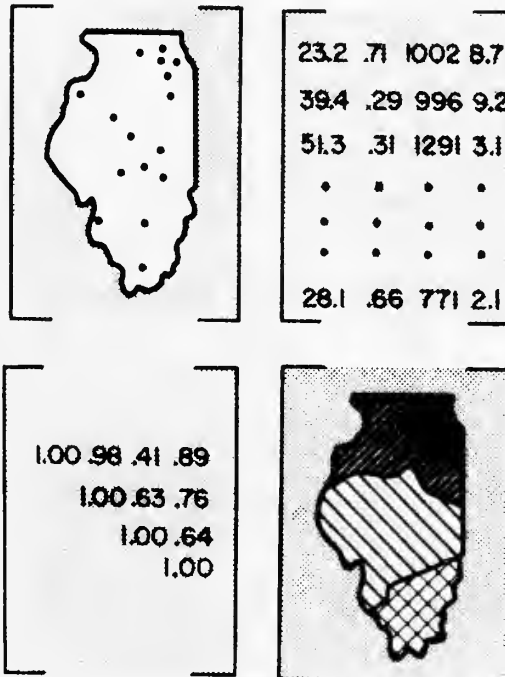
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GLACIAL MAXIMUM TUNDRA: A BIOCLIMATIC ANOMALY

by

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GLACIAL MAXIMUM TUNDRA: A BIOCLIMATIC ANOMALY*

Joseph M. Moran**

ABSTRACT

The periglacial fossil record of late Wisconsinan time indicates that tundra and permafrost occurred sporadically in a narrow zone adjacent to the edge of the Laurentide ice sheet. This belt of frigid conditions was an anomalous component of the environment of unglaciated North America where evidence from most regions suggests relatively mild winters. It is here proposed that the resulting contiguity of sharply contrasting climatic zones can be explained by exclusion of Arctic air from periglacial North America and by modified katabatic winds at the glacier margin.

INTRODUCTION

Recently Williams *et al.* (1974) reported on their use of the NCAR global circulation model to reconstruct atmospheric circulation patterns of the last Glacial maximum (*circa* 18,000 BP). Input of Glacial maximum boundary conditions (including reconstructed orography, land surface albedos and ocean surface temperatures) yielded January and July patterns that differ significantly from reconstructions based upon other techniques (*e.g.*, Lamb and Woodroffe, 1970). While application of numerical models in this way promises to provide valuable insights into the nature of past climates and climatic change, it warrants some critical review, especially at this early stage of use.

One notable difficulty with the Williams *et al.* study is the failure of their reconstruction to resolve a pronounced climatic zonation that is delineated by the composite of periglacial fossil remains. Mounting evidence supports the notion that during late Wisconsinan time the Laurentide ice

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sheet was bordered by a narrow zone of tundra or taiga-tundra. However, the severe cold that supported this paleobiome was probably an anomalous feature of the periglacial environment since the fossil data from the remainder of unglaciated North America suggest that winter climatic regimes were relatively mild. The resulting contiguity of contrasting climatic zones gave rise to a locally steep surface meridional temperature gradient that is unresolved in the findings of Williams *et al.*

This paper reviews the fossil biotic and physical evidence for this climatic zonation and offers a possible explanation for its development.

BIOTIC AND ABIOTIC EVIDENCE

Based upon a synthesis of available data from the last Glacial maximum, Brunnschweiler (1962) proposed that periglacial frozen ground and associated tundra extended several hundred kilometers south of the Laurentide ice front on the western high plateaus, on the higher Appalachian peaks and perhaps even along the Atlantic coastal plain. However, as additional data are uncovered, and as new and old evidence is subjected to more critical examination than formerly possible, it appears that a somewhat more conservative estimate of late Wisconsinan tundra and permafrost distribution is in order. Biotic and abiotic fossil evidence that unequivocally indicates the former presence of tundra and permafrost is confined to a few localities in the Appalachian uplands and to a narrow zone (perhaps only 50 to 150 kilometers wide) along the Laurentide ice margin.

Examples of micro-fossil (pollen) and macro-fossil floral evidence of tundra and taiga-tundra are summarized in Table 1. Information on late Wisconsinan vegetation in regions south of the ice sheet is meager primarily because of the small number of suitable sampling sites. Nonetheless, there

TABLE 1. Micro-Fossil (Pollen) and Macro-Fossil Evidence of Late Wisconsinan Tundra and Taiga-Tundra East of the Rocky Mountains of North America.

G = Glaciation

<u>LOCATION</u>	<u>EVIDENCE AND INDICATION</u>	<u>DATE</u>	<u>REFERENCE</u>
Southern St. Louis County, Minnesota	Tundra Vegetation Plant Macro-fossils	12,000-10,500 BP	Baker, 1965
Cambridge, Massachusetts	Arctic or Alpine Plant Macro-fossils	12,800-10,400 BP	Argus and Davis, 1962
Chester County, Pennsylvania	Pollen: Tundra and Taiga-Tundra	G to 13,500 BP (?)	Martin, 1958
Southern Connecticut	Pollen: Tundra and Park-Tundra	G to > 13,500 BP	Leopold, 1956
Central Massachusetts	Pollen: Tundra	G to > 13,000 BP	Davis, 1958
Martha's Vineyard, Massachusetts	Pollen: Park-Tundra and Tundra	G to > 15,000 BP	Ogden, 1959
Eastern Long Island, New York	Tundra (?)	G to > 13,500 BP	Donner, 1964
Arroostook County, Maine	Pollen: Tundra	Late Glacial	Deevey, 1951
Buckle's Bog, Maryland	Pollen: Treeless Tundra	18,500-12,700 BP	Maxwell and Davis, 1972
Moulton Pond, Maine	Pollen: Tundra	14,000-9,700 BP	Davis <i>et al.</i> , 1975
Madelia, Minnesota	Pollen: Tundra	Late Glacial	Jelgersma, 1962

* * * * *

is sufficient information available to permit a tentative delineation of late Wisconsinan tundra distribution in unglaciated eastern North America. In a summary of major late Glacial pollen zonations from southeastern Pennsylvania through southern New England, Sirkin (1967) describes a typical deglaciation biotic sequence of taiga-tundra followed by spruce forests. Maxwell and

Davis (1972) report that during the last full-glacial episode, tundra extended at least as far south as Buckle's Bog, Maryland (at only 800 meters elevation) on the Allegheny plateau, with Alpine tundra probably having extended further south on higher peaks of the Appalachians. In addition, Whitehead's (1973) reconstruction of full-glacial vegetational patterns in unglaciated eastern North America shows a narrow zone of tundra and taiga sandwiched between the ice margin and a broader spruce-dominated conifer forest to the south.

In polar latitudes there is today an association of tundra with cryostatic features that are products of permafrost activity. Although permafrost underlies many modern tundra areas, fossil evidence of tundra does not unequivocally mean that permafrost was also present. Further, uncovering evidence of past permafrost is not without its pitfalls. Fossilized remains of pingos and ice-wedges (and the latter's surface expression as polygonal patterns) appear to be the most reliable indicators of the former presence of permafrost (Péwé, 1973). With optimal development, several other types of relic features, including rock glaciers and cryoplanation terraces, may have had a genetic relationship to permafrost. In any event, errors may arise in both the initial interpretation of ground features as cryostatic, as well as in ascribing their origin to permanently frozen ground. As an example of the former, fossil ice-wedges, unless examined in three dimensions, may be confused with soil tongues (Yehle, 1954) or desiccation crack fillings (Smith, 1949). Péwé (1973) attributes this problem to investigators' unfamiliarity with modern permafrost features. As an illustration, ground involutions were considered by many Quaternary environmentalists to be indicative of the former presence of perennially frozen ground. However, Mickelson and Evenson (1974) point out

that recent work conducted primarily in Russia and Poland demonstrates that many fossil involutions can be explained by mechanisms other than freeze-thaw phenomena within the active layer above ground ice. For example, Mickelson and Evenson attribute numerous involutions on the upper surface of red till (late Wisconsinan) north of Manitowoc, Wisconsin, to loading stresses produced by deposition of lacustrine sands over till.

In spite of difficulties in interpretation, there are numerous reliable reports of late Wisconsinan permafrost indicators from localities along the former periphery of the Laurentide ice sheet in North America. While ongoing field studies are likely to add to the compilation in Table 2, the evidence is now sufficient to conclude that conditions conducive to frozen ground formation were confined to the immediate vicinity of the glacier margin. Characteristically, relic frozen ground phenomena of late Wisconsinan age are interpreted to have developed in (1) unglaciated regions near the ice front or (2) in drift during deglaciation. In contrast, modern permafrost extends hundreds of kilometers beyond glacial masses.

A narrow tundra or taiga-tundra zone underlain at least sporadically by permafrost lends support to the proposal that severely cold conditions existed adjacent to the Laurentide ice front. As is the case with phenomena that are products of the interactions of many variables, maintenance of permafrost conditions may be explained by certain modes of behavior among various edaphic and climatic parameters. However, there are suggestions of a much simpler permafrost-climate relationship: Preservation of consolidated or unconsolidated ground material at temperatures below freezing throughout the year, requires a mean annual air temperature no higher than -1°C (Black, 1954; Brown, 1965; Péwé *et al.*, 1965). This threshold temperature is, however, not a

TABLE 2. Late Wisconsinan Periglacial Frost Phenomena in North America
(Compilation after Moran, 1972, and Péwé, 1973).

LOCATION		ICE WEDGES	PINGOS	INVOLUTIONS	POLYGONAL PATTERNED GROUND	REFERENCE
WASHINGTON	Thurston				X	Péwé, 1948; Newcomb, 1952; Ritchie, 1953
MONTANA	Windham			X		Schafer, 1949
	Great Falls			X		Schafer, 1949
	Stanford			X		Schafer, 1949
	Choteau			X		Schafer, 1949
	Vaughn	X				
NORTH DAKOTA	Southwestern	X				Clayton and Bailey, 1970
IOWA	Central	X				Wilson, 1958
	Tama Co.				X	Ruhe, 1969
ILLINOIS	DeKalb		X			Flemal, Hinkley, and Hesler, 1973
	Coal City			X		Sharp, 1942
	Peoria Co.			X		Frye and Willman, 1958
	Henry Co.			X		Frye and Willman, 1958
	Woodford Co.	X				Frye and Willman, 1958
	Bureau Co.	X				Horberg, 1949
WISCONSIN	West-Central (>200 sites)	X				Black, 1965
INDIANA		X?	X?		X	Wayne, 1967
OHIO	Richland	X				Péwé, 1973
	Western	X?		X		Goldthwait, 1959
NEW JERSEY	Roebling			X		Wolfe, 1953
	Palmyra	*X				Wolfe, 1953
CONNECTICUT	Stratford	*X?		X		Denny, 1936
RHODE ISLAND	North Scituate	*X			X	Birman, 1952
ONTARIO	Kitchener	X			X	Morgan, 1972
QUEBEC	Southern (>300 sites)	X				Dionne, 1975
NOVA SCOTIA	Northern	X				Borns, 1965
NEWFOUNDLAND	Western	X				Brookes, 1971

*Doubtful interpretation according to Péwé (1973)

?Investigator unsure of interpretation

universally accepted criterion, apparently because of the difficulty experienced by some investigators in differentiating permafrost that is in response to present climate from permafrost residual of past climatic episodes.

The sporadic distribution of late Wisconsinan fossil permafrost indicators suggests an environment analogous to that which exists today in the discontinuous permafrost zones of Alaska (Péwé *et al.*, 1965) and Canada (Brown, 1969). Hence, annual air temperatures adjacent to the Laurentide ice margin probably averaged between -1°C and -5°C . However, in the sheltered environment of interlobate regions where unglaciated terrain was surrounded on three sides by glacial ice, temperatures plunged to levels sufficient to support ice-wedge activity. An example is the Driftless Region of southwestern Wisconsin, where numerous well-developed ice-wedge casts indicate more continuous permafrost and annual temperatures of less than -5°C (Black, 1965). Colder conditions appear reasonable in view of the sheltered environment fostered by the confinement of the Driftless Region by the Lake Michigan and Des Moines Lobes, and are in agreement with Péwé's opinion (1973) that modern ice-wedge formation requires mean annual air temperatures of -6°C to -8°C or lower.

If the difference between full-glacial and modern climate patterns simply involves a southward displacement of climatic-ecological zones ahead of the advancing ice sheet, then late Wisconsinan evidence of boreal forest should be found to the south of the taiga-tundra belt. However, while pollen profiles to the south do indicate that forest communities were dominated by boreal species, full-glacial forests differed significantly in total species composition and abundance from the modern boreal forest of Canada. For

example, Maxwell and Davis (1972) note that, while fir is an abundant component of the modern boreal forest of eastern Canada, it was a minor element in the forest communities of eastern North America during late Wisconsinan time. Also, full-glacial palynological evidence from western Missouri (King, 1973) and southern Illinois (Grüger, 1972) indicate that temperate deciduous trees were present in low numbers along with boreal elements.

Differences between the modern and full-glacial boreal forests may have important paleoclimatic implications. Bryson (1966) demonstrated that the modern boreal forest is geographically delineated by Arctic air, *i.e.*, the boreal forest is situated between the summer and winter modal positions of the Arctic front. However, the presence of temperate deciduous taxa in the full-glacial boreal forest would appear to preclude Arctic air dominance. Hence, the reconstructed vegetational zonation south of the Laurentide ice margin suggests a rather drastic transition from frigid tundra to a considerably milder zone of conifer forests.

Faunal evidence also indicates that in the midsection of the United States, late Wisconsinan time was characterized by colder, but not severe, conditions. Frye and Willman (1958) report that abundant snail fauna are found in Peoria loess in Illinois--in some cases within fifteen kilometers of the former glacier margin. Available mollusk remains in late Wisconsinan loess suggest a cooler and moister environment than at present and a lack of extremes in summer temperatures. Along the 35° latitude circle from Blackwater Draw, New Mexico, through Texas and into Oklahoma (Bryson and Wendland, 1966; Slaughter, 1967), late Glacial fauna indicate that winters were not more severe than at present and probably were somewhat milder. Mild periglacial conditions were further substantiated by the conspicuous absence

of cirques in the southern Appalachians of Tennessee and North Carolina, where many peaks exceed 2,000 meters in elevation.

PROPOSED MECHANISM

The biotic and abiotic evidence summarized above suggests that during late Wisconsinan time an anomalously steep meridional temperature gradient prevailed immediately south of the Laurentide ice margin. This steep temperature gradient constituted a transition between a narrow zone of extremely cold air adjacent to the glacier toe and a broad region of considerably milder conditions to the south. A possible explanation for this climatic contrast is arrived at upon examination of certain physical characteristics of contemporary glaciers.

Regardless of irregularities in underlying topography, the Antarctic and Greenland ice sheets exhibit a fixed equilibrium profile (Robin, 1962). From this observation the vertical dimensions of the Laurentide ice sheet can be estimated from its known areal extent (Moran and Bryson, 1969). Such an analysis indicates that in places the crest of the Laurentide glacier may have been 3 kilometers above sea level. The climatic implications of an ice ridge of this magnitude stretching from the Cordillera to the Atlantic are imposing. As pointed out by Bryson and Wendland (1966), the Laurentide ice sheet was sufficiently massive to bar the southward spread of Arctic air. Exclusion of Arctic air from regions south of the ice front is one factor that contributed to mild winter conditions and the establishment of conifer forest communities that have no modern analogue.

Another moderating factor is evident upon review of the effect of modern ice sheets upon wind regimes. A shallow (less than 500 meters deep),

sometimes violent, gravity flow of air is typical along the sloping ice plateaus of Greenland and Antarctica (Lettau, 1966). This katabatic wind is independent of the regional gradient circulation and is particularly well developed at the glacier periphery where slopes are steepest. It is suspected that radial katabatic winds also characterized the Laurentide ice sheet.

As it flows downhill, the katabatic wind undergoes compressional warming. Hence, cold air originating at the crest of the Laurentide glacier experienced considerable modification as it flowed downward toward unglaciated portions of North America. Because in late Wisconsinan time, as now, there was a gradual slope in elevation from the Atlantic coast through the Great Plains, it appears that the magnitude of adiabatic warming decreased from east to west--the ground to ice-crest distance being less to the west. On the basis of the present land slope and reconstructed Laurentide maximum ice elevation of 3 kilometers, the expected warming due exclusively to compressional flow varies from 30 C° on the Coastal Plain, to 28 C° in extreme western Iowa and the eastern Dakotas, and down to under 22 C° at the Front Range of the Northern Rockies. These values, however, may be underestimates in view of the fact that modern mean monthly temperatures of coastal Antarctic stations are somewhat warmer than they would be if air temperatures were determined exclusively by adiabatic compression of air from the ice crest. As an illustration, mean monthly temperatures for the years 1957-60 at Halley Bay (75° 31'S, 26° 26'W) and McMurdo (77° 50'S, 166° 36'E)--both coastal stations--were compared to temperatures estimated from adiabatic compression of air from Admunsen-Scott--located at the South Pole. For the coldest six of the year (April through September), actual monthly mean temperatures

averaged 5.9 C° warmer than adiabatic at Halley Bay and 6.5 C° warmer than adiabatic at McMurdo.

Exclusion of Arctic air coupled with modification of glacial crest air favored non-severe winters south of the ice sheet. Also, it is likely that full-glacial Pacific air and Gulf of Mexico air differed little in thermal characteristics from their modern counterparts, simply because the physical properties of their source regions during late Wisconsinan time were not significantly different from those of today. Hence, air masses which invaded unglaciated regions could not have produced winter conditions more severe than observed today, and, in fact, winters may have been somewhat milder.

However, from observations of katabatic flow in Greenland and Antarctica (Ball, 1957), it is probable that within the lowest layers of a katabatic air stream the combination of suspended ice and snow particles and the heat sink provided by the ice surface would be sufficient to compensate for compressional warming. Hence, it is here proposed that on the Laurentide ice sheet a very shallow ice-contact flow of extremely cold air was maintained along the glacier surface and down to its margin. There, cold air accumulated as a wedge, giving rise to conditions conducive to tundra and permafrost development. It is also suspected that in those localities sheltered from regional winds (*e.g.*, interlobate areas), temperatures were sufficiently low to favor ice-wedge formation.

Development of a pocket of anomalously cold air adjacent to the Laurentide ice front gains some credibility from an observation by Geiger (1965, pp. 414-415), who describes a comparable wedge of cold air at the margins of modern alpine glaciers. This localized wedge of air creates a significant

altitudinal depression of vegetation at the glacier toe, and is maintained by a shallow (10 to 20 meters), down-slope, ice-contact, *firn wind*. In addition, vertical wind profiles computed for Antarctica (White and Bryson, 1967) suggest that a cold air pocket may develop at the margins of continental as well as mountain glaciers (Figure 1). Characteristically, air flow is light and variable at the Antarctic glacier toe, and then increases in speed with height to a maximum near the 800-mb level, and then decreases again with height. The zone of strongest meridional flow slopes downward away from the ice margin and may define the upper boundary of the glacier-maintained cold air wedge.

SUMMARY AND CONCLUSIONS

Both biotic and abiotic fossil evidence from North America suggest that a locally steep meridional air temperature gradient existed in a zone peripheral to the Laurentide ice sheet during late Wisconsinan time. This abrupt north-south temperature change was apparently in response to exclusion of Arctic air from unglaciated North American and to the opposing effects of two air flow regimes (Figure 2) that were the consequence of Laurentide glacial feedback upon climate:

- (1) a shallow, cold ice-contact *firn wind*, and

- (2) adiabatically modified katabatic flow of glacial crest air.

The result was the contiguity of a severely cold tundra zone and a milder conifer forest zone to the south.

It is expected that the simple model proposed here will be verified, modified or rejected on the basis of a numerical simulation which is currently under development.

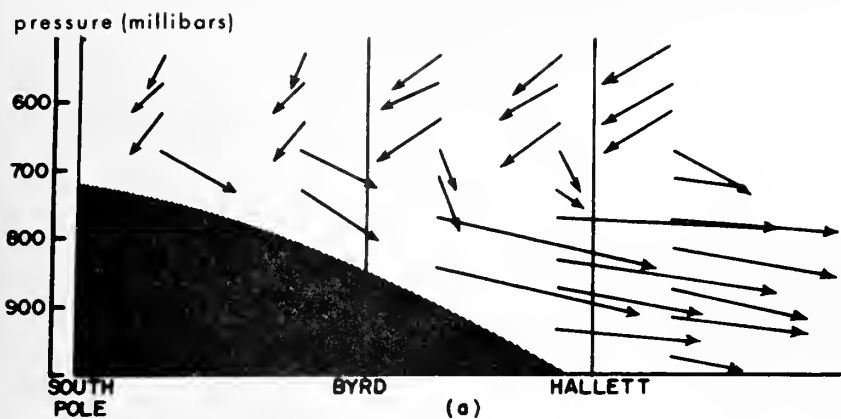


FIGURE 1.

Estimated meridional circulation patterns for Antarctica for (a) April-May, (b) June-July, and (c) August-September. After White and Bryson, 1967.

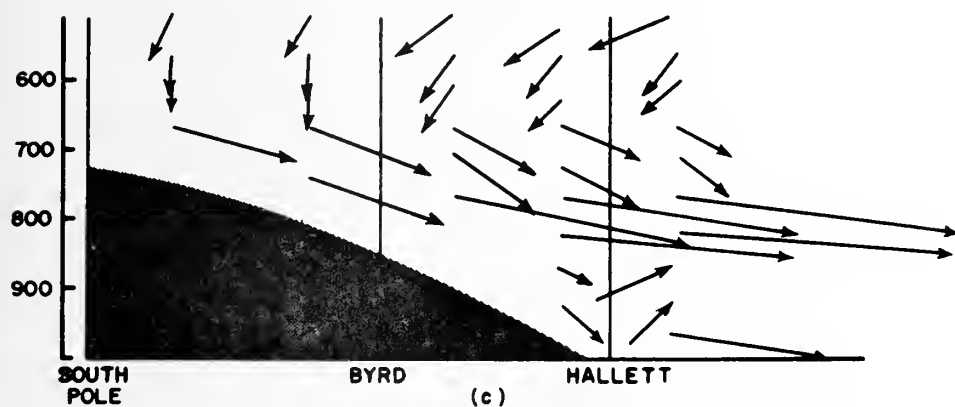
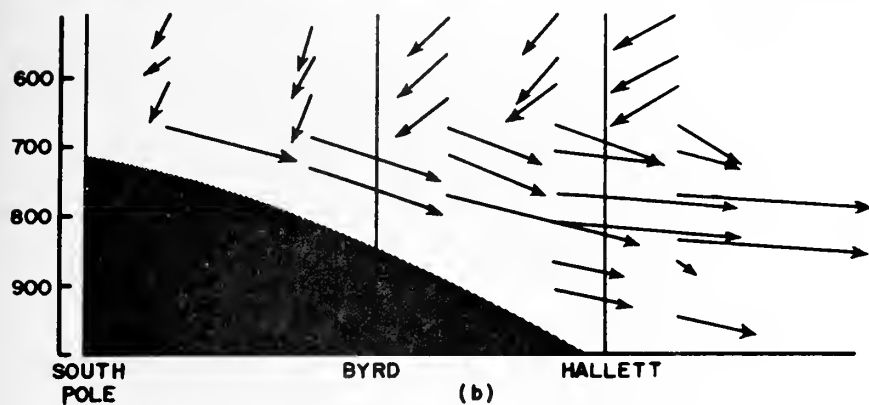
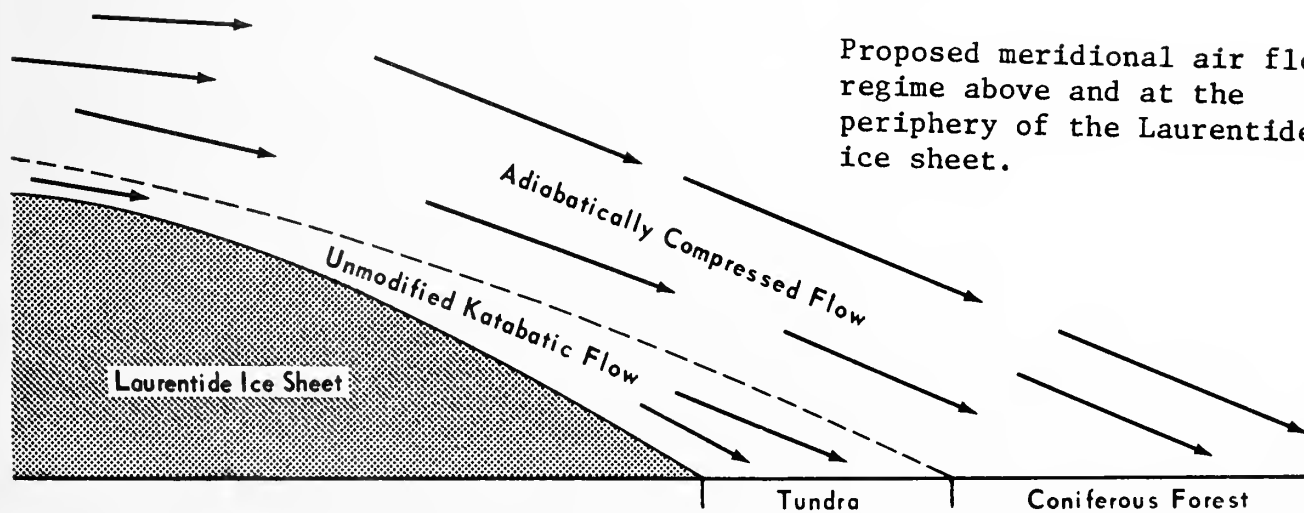


FIGURE 2.

Proposed meridional air flow regime above and at the periphery of the Laurentide ice sheet.



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